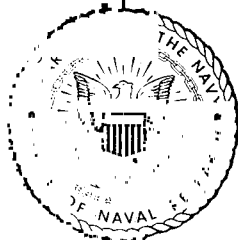# VISUAL MEASUREMENTS OF ATMOSPHERIC
TRANSMISSION OF LIGHT AT NIGHT

NAVAL   RESEARCH   LABORATORY

WASHINGTON, D.C.

VISUAL MEASUREMENTS OF ATMOSPHERIC TRANSMISSION OF LIGHT AT NIGHT

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Approved by:

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ABSTRACT

Measurements of the visual transmission of the atmosphere were made at night across Chesapeake Bay over a period of two years. A visual telephotometer was used to measure the illumination produced at a distance of 8.77 sea miles by a series of calibrated light sources. Transmission values ranging between 0.4 and 0.9 per sea mile could be measured to an accuracy of ±2 percent with the equipment as installed. Lower values were outside the range of the equipment and higher values are not normal for transmission through air. Under stable atmospheric conditions the data obtained at night were in good agreement with direct observations of the daylight visual range made before sunset and after the following dawn.

PROBLEM STATUS

This is a final report on one phase of the problem; work is continuing on other phases.

AUTHORIZATION

NRL Problem N03-14R
NR 473-140

VISUAL MEASUREMENTS OF ATMOSPHERIC TRANSMISSION OF
LIGHT AT NIGHT

INTRODUCTION

The transparency of the atmosphere for visible light can be determined with moderate accuracy during the daytime from observations of daylight visual range using large, dark, distant objects (1). Daylight visual range is the maximum distance at which a black object, subtending an angle greater than about 0.5° at the observer, can be seen against the sky at the horizon. At night, however, there is no such simple way of making accurate estimates of atmospheric transparency and observers usually go by their subjective impression of the brightness of distant lights or objects. Accurate data concerning the visual transparency of the atmosphere at night are important for (a) field studies of near infrared image-forming equipment; (b) optical communication systems; (c) optical aids to night vision; and (d) correlating atmospheric attenuation in nonvisible spectral regions with that in the visible. This report does not deal with the practical applications but only with the methods of instrumentation and results of atmospheric transmission studies at the Chesapeake Bay Annex.

Although the transmission of the atmosphere in spectral regions other than the visible is of considerable interest, the first equipment installed was designed to work in the visible portion of the spectrum. This decision was made because the visual transmission of the atmosphere is the most natural and meaningful single parameter in terms of which the light transmitting properties of the atmosphere can be specified. Since it is the visual transmission which goes hand in hand with everyday experiences, it is in terms of visual transmission that practical thinking about atmospheric clarity is generally carried out.

An earlier method used by NRL for obtaining atmospheric transmission at night was to observe the daylight visual range before dark and to assume that the atmosphere did not change transparency after sunset. However, it was often obvious that the transparency did change, and therefore it was necessary to develop a nighttime measuring system.

The condition of particular interest was clear weather corresponding to daylight visual ranges greater than three sea miles. For accurate measurements under these conditions it was necessary to use a long light path. When measurements are made over water, conditions are usually quite uniform and present a closer approach to naval problems.

The Chesapeake Bay Annex of the Naval Research Laboratory (2) offered ideal conditions for work on atmospheric transmission and field tests of optical equipment. The Annex is about 30 miles from the Naval Research Laboratory, Washington, D. C.,and is situated on a cliff directly overlooking the Bay at an elevation of 100 feet above sea level (Figure 1). Eight and three-quarters sea miles east across Chesapeake Bay is located Tilghman Island with field facilities consisting of two 100-foot towers three quarters of a mile apart. The eight-and-three-quarters-mile range across the Bay provided a path of

suitable length for measurements of visual atmospheric transmission at night in clear
weather. The measurements of atmospheric transmission were made during a period
of about two years.

Figure 1 - Chesapeake Bay Annex as seen from the Bay

THEORY

The transmission of light through the atmosphere from a source of small dimensions
can be represented by the equation:

$$E = E_0 e^{-\beta x} \tag{1}$$

where E = illumination at a distance x from a light source of small dimensions compared
with the distance x, β = atmospheric attenuation coefficient, and E_0 = illumination at a
distance x if there were no atmospheric attenuation.

Since $E_0 = C/x^2$, where C = candle power of the light source, and $e^{-\beta} = t$ is the
fraction of light transmitted per unit distance, Equation 1 can be written as $E = (Ct^x)/x^2$.
Solving this equation for t,

$$t = (Ex^2/C)^{1/x} \tag{2}$$

which is the equation used for calculating the transmission per unit distance from the
measurements of the illumination E, the distance x, and the candle power C.

The method used to determine t was to measure, by means of a visual telephotometer,
the illumination produced at a known distance, x, from a light source of known candle power.
By means of Equation 2 the transmission per sea mile was calculated. In practice, graphs
for the several light sources used, and for the fixed distance of 8.77 sea miles, showed
transmission per sea mile versus illumination in sea-mile candles.

In the daytime, the above method cannot be used because the illumination is too low to be measured in the presence of a bright background. The value of t can be deduced quite simply, however, from the daylight visual range. It has been shown (1) that

$$V\beta = \ln \frac{1}{\eta} \tag{3}$$

where η = threshold of brightness contrast which is about 0.02 for the usual intensities of daylight illumination, V = daylight visual range, and β is the atmospheric attenuation coefficient ($t = e^{-\beta}$). The proper value of η is subject for research in itself and is still not settled. Middleton (3) states that η has the values 0.01 to 0.02 for ordinary daylight illumination and Douglas (4) found 0.055 to be the best value for fog. In general, the value of the threshold brightness contrast is a function of the angle subtended at the eye by the object viewed, the contrast between the object and the surroundings, and the illumination level.

EQUIPMENT

The equipment set up to measure the visual transmission of the atmosphere consisted of several calibrated light sources of considerable intensity located on Tower No. 1 at Tilghman Island, and, at the Chesapeake Bay Annex, two Maxwellian-view type of telephotometers to measure the illumination received from the light sources. Electronic telephotometers were avoided for the sake of extreme simplicity.

The Maxwellian-view telephotometers, constructed by a simple modification of existing photometers, are described in detail in a previous report (5). One such telephotometer, a modified Macbeth illuminometer, had a Maxwellian-view attachment consisting of an objective lens cut from a spectacle lens and slipped into the entrance tube of the illuminometer (Figure 2). The lens power was such that a distant light source was imaged on the observer's eye pupil so as to form an out-of-focus patch of light on the retina. The brightness of this patch was proportional to the light flux entering the objective lens from the distant source. Since this patch was surrounded by the comparison field of the illuminometer, a brightness match could easily be made and a quantitative measure of the light flux would be obtained. An aperture of small size was placed over the eyepiece directly before the eye to decrease the field of view of the telephotometer and to make sure that the photometric match was unaffected by closure of the observer's pupil. By using apertures of different sizes the range of measurement covered by the instrument was extended.
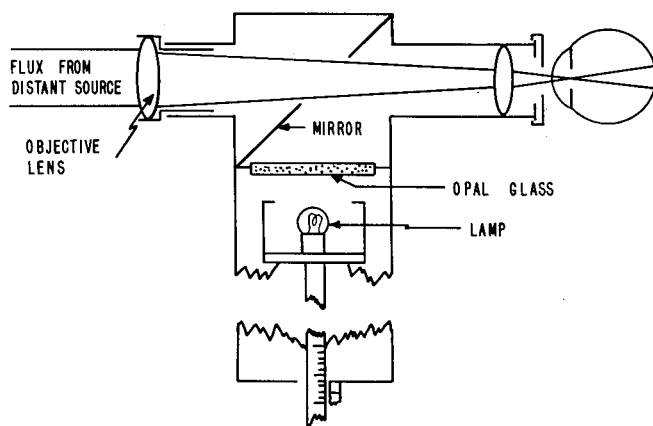

Figure 2 - Maxwellian-view telephotometer modification of Macbeth illuminometer

The other telephotometer (Figure 3) was basically a low-brightness photometer of the type developed at the University of Rochester (6). Here the comparison source was a luminescent phosphor. In one model the phosphor was excited by a radium-containing gold foil and in another model this was replaced by a luminous phosphor button. The phosphor, carried on the end of a swinging arm, illuminated an opal glass which was the actual comparison field. This opal glass was viewed in a small 45° mirror. The Maxwellian attachment in this case consisted of two objective lenses. The first imaged the distant source on an iris diaphragm and the second brought the beam to a focus at the eye pupil. The iris diaphragm served as a variable field stop to reduce the field of view when the background around the distant light source was bright. Again the final aperture had to be smaller than the observer's pupil so that the changes in the size of the pupil would not affect the photometric match. The entire unit was tripod-mounted (Figure 4).
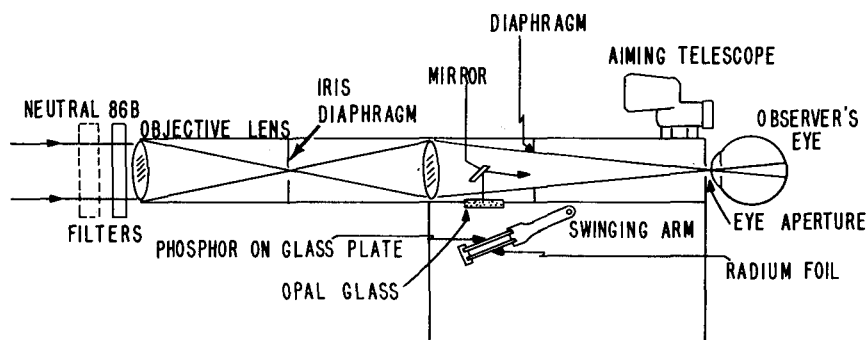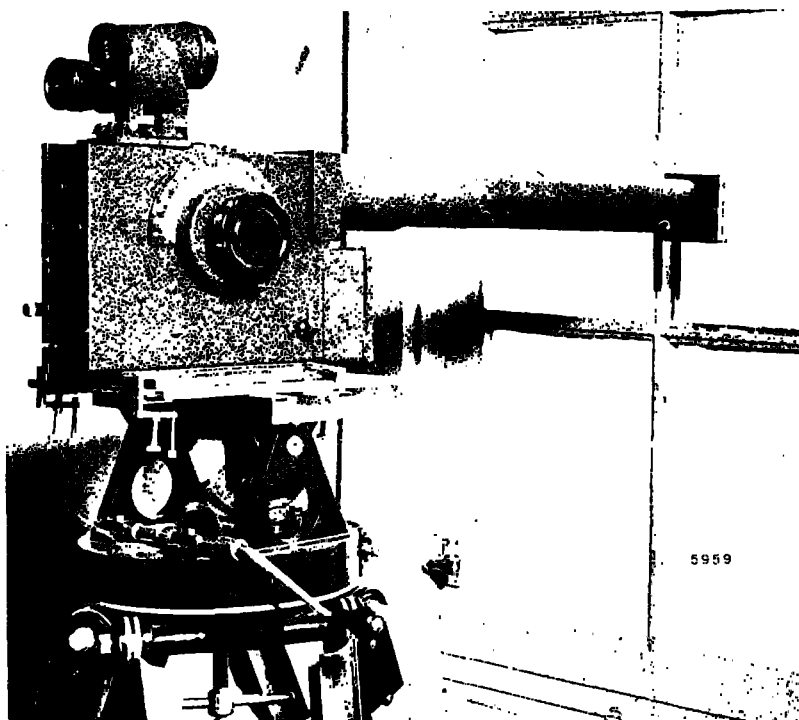

Figure 3 - Phosphor-type Maxwellian-view telephotometer

Figure 4 - Phosphor-type Maxwellian-view telephotometer in observing position

The light sources used were of two types: filament lamps of about 1000 candle power used in pairs to double the total intensity, and 12-inch Navy searchlights with spread lens, having a beam candle power of about 90,000. The searchlights were equipped with an accurate sight for aiming at the telephotometers. One installation, a pair of filament lamps and a searchlight, was made at the top of the Tilghman Island tower (Figure 5) 115 feet above sea level, and a second similar installation was made at 32 feet. The telephotometers were located in the highest penthouse of the Chesapeake Bay Annex test control tower at an altitude of 149 feet.
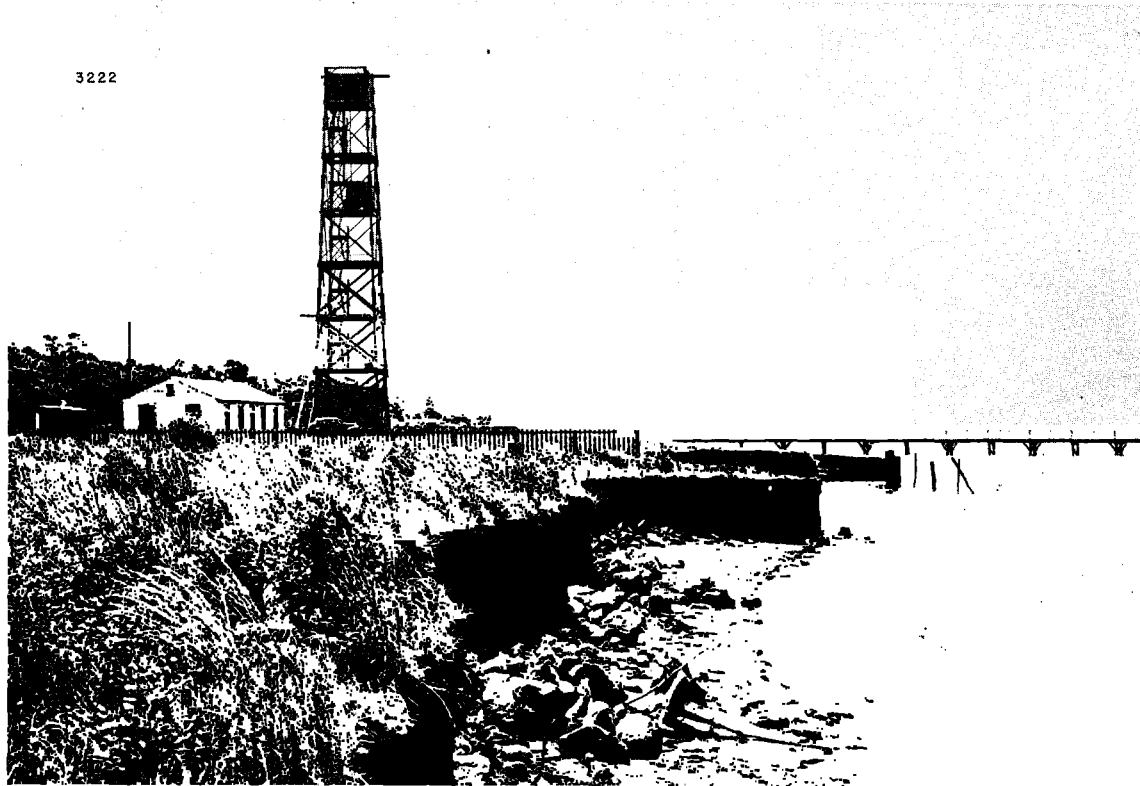
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Figure 5 - Tower No. 1 on Tilghman Island

CALIBRATION

The candle powers of the several light sources were measured in the laboratory in the particular direction at which the light was to be observed. The lamps were calibrated for candle power at 2850°K by comparing them with National Bureau of Standards standard lamps, except for the searchlights, which were measured with a carefully calibrated Macbeth illuminometer. Voltage regulators were used with the light sources at Tilghman Island; and, by means of a Variac, an operator maintained a constant ammeter reading during operation.

The telephotometers were calibrated against a reference light source of known candle power operated at 2360° K color temperature, in accordance with practice which is now

generally accepted in low-brightness photometry. The reference light source consisted of a Macbeth illuminometer lamp operated with the control unit furnished with the instrument. This light source was calibrated for candle power in terms of a National Bureau of Standards lamp. The calibration procedure for both types of telephotometers was as follows:

a) The standardized lamp was placed at one end of the NRL light tunnel, about 130 feet long, with the telephotometer at the other end.

b) Rotating sectored discs were used to attenuate the light source.

c) The telephotometer was pointed so that the lamp filament was imaged properly in the eye aperture, and the observer, after 30 minutes of dark adaptation, made several readings with the telephotometer for each illumination level produced at the objective lens by the light source and rotating sectored discs.

d) Wratten neutral filters of about density 1 and 2 were used with the telephotometer to extend its range.

e) Calibration graphs were prepared giving illumination in sea-mile candles versus telephotometer readings for use in the field.

All the light sources on Tilghman Island were operated at a color temperature of $2850^\circ K$, and Wratten 86B filters of known transmission were placed in front of the telephotometers to reduce the color temperature to $2360^\circ K$. This resulted in a higher intensity than would have been obtained if the sources themselves had been operated at a color temperature of $2360^\circ K$. The transmission of the 86B filters was taken into account when preparing the calibration graphs of the telephotometers. Most of the measurements were made with the self-luminous button type of telephotometer since it was easier to operate than the Macbeth.

MEASUREMENT AND ANALYSIS

The equipment was first placed in operation in 1947. This report presents measurements made on 120 nights spread over a period of approximately two years. The frequency distribution of the atmospheric transmission measurements is shown in Figure 6. The clearest night observed had a transmission of 0.92 per sea mile and more than half the nights had a transmission greater than 0.8 per sea mile. The equipment was unable to measure transmission values lower than 0.4 per sea mile. This value corresponded to a transmittance over the range of about 3/10,000 of the original light flux. For transmittance values much less than 0.4, the 12-inch searchlight was invisible and no measurements could be made. Thus the frequency diagram in Figure 6 is slightly distorted because of the exclusion of nights having transmission below 0.4 per sea mile. The frequency of occurrence of such nights was low; therefore, it was concluded that Figure 6 gives a fairly accurate picture of nighttime transmission over Chesapeake Bay.

Figure 7 shows a similar frequency diagram of daytime transmission over Chesapeake Bay, the transmission in this case being derived from observations of daylight visual range. Transmissions below 0.4 per sea mile are included in this diagram; however, it will be seen that few days had values this low. This confirms the conclusion that Figure 6 is not distorted appreciably by the exclusion of nights having a transmission of less than 0.4 per sea mile.

Records were kept of relative humidity, barometric pressure, temperature, and wind velocity and direction. No correlation of any of these data with atmospheric transmission was found.

It was of interest to correlate the transmission measured at night with the daylight visual range observed during the previous and following days. This was attempted only when atmospheric conditions seemed to be stable. Daylight visual ranges were observed before sunset and after the following sunrise; then data were compared for days when the pre-sunset and post-dawn ranges were the same.

In Figure 8 the attenuation coefficients measured at night are plotted against the daylight visual ranges. Straight lines representing Equation 3 are drawn for threshold constants, η, of 0.01, 0.02, and 0.05. It can be seen that the observed points fall reasonably well on the 2-percent line

Figure 6 - Frequency distribution of atmospheric transmission values based on 120 nights of measurement across Chesapeake Bay (1947-49)

and that no points lie outside the 1- and 5-percent lines. At the longer ranges, however, there seems to be a trend toward the 5-percent line. This can be explained qualitatively by the fact that for long ranges the distant shore line, which was the target observed, subtended a very small angle to the eye and this probably required a contrast of greater than 2 percent in order to be visible. Daylight visual ranges greater than 20 sea miles could not be determined because available tragets were not large enough to be seen. The conclusion was that the agreement between the two methods was satisfactory when atmospheric conditions were reasonably stable.

It should be noted that the visual range of lights at night is not the same as the daylight visual range. The former, of course, depends on the intensity of the light. For the same transmission per sea mile, a strong light can be seen much further at night than a large black object can be seen in the daytime.

The question is raised as to whether the transmission close to the water is the same as that along the path some distance above
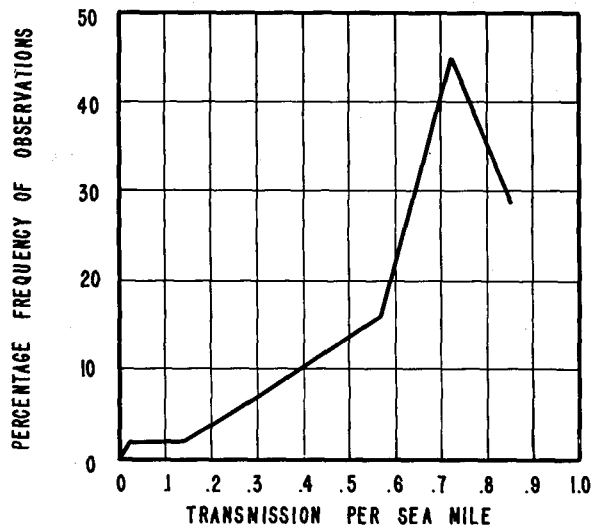

Figure 7 - Frequency diagram of atmospheric transmission at Chesapeake Bay Annex, based on 345 days of observation of daylight visual range (Oct. 15, 1948 -Oct. 14, 1949).
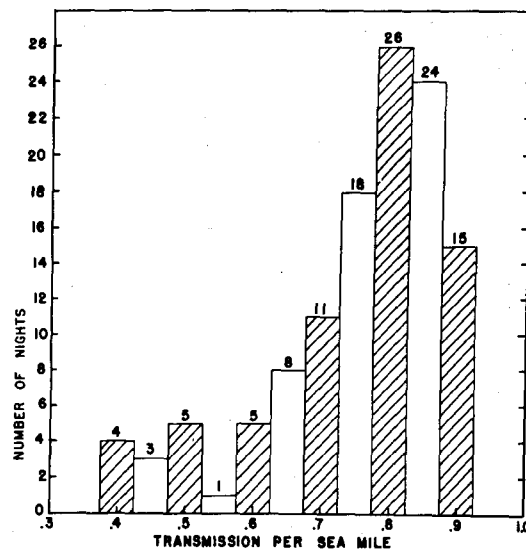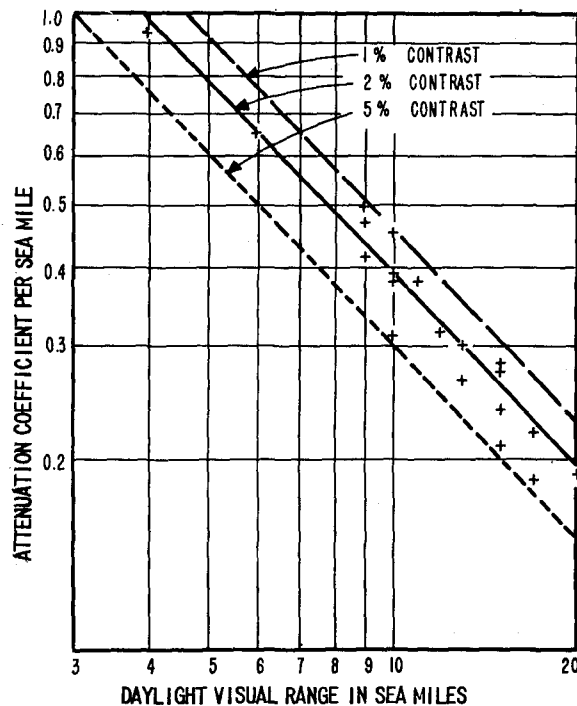
Figure 8 - Comparison between the measured attenuation coefficient and the observed meteorological range

the water. This was investigated by comparing the data obtained with the light sources located 115 feet and 32 feet, respectively, above the water. The telephotometers at the opposite side of the Bay were kept at 149 feet above sea level. The experimental results given in Table 1 show approximately the same transmission for both light paths. On a few occasions the telephotometers were carried down to the water's edge (20-foot elevation) and still no appreciable difference was observed. However, the averages of all the values for the 115-149 feet, 32-149 feet, and 32-20 feet paths, respectively, indicate that the transmission was very slightly greater for the paths at higher elevation. Hence, these results show that under ordinary conditions stratification over this range occurred but was negligibly small.

Refractive effects have been noticed under certain special conditions. It was observed, for example, on one occasion when making measurements near the water level, that the lower searchlight could be seen clearly at a certain elevation while a few feet lower the searchlight could hardly be seen at all and no measurements were possible since changes were taking place rapidly.

Twinkling of the light sources was usually conspicuous and under these conditions an average photometric match was made. Settings were also attempted on the brightest and dimmest flashes; the ratio of illumination measurement for the brightest to the dimmest setting was often 2 and occasionally as high as 4. The study of twinkling has been done in great detail by E. Goldstein of this Laboratory (7,8).

Tables 2 and 3 illustrate typical data and results for nights of stable and turbulent atmospheric conditions, respectively.

TABLE 1
Atmospheric Transmission Versus Elevation of Path

Date of Reading	Transmission Per Sea Mile		
	Source 115 ft Telephotometer 149 ft	Source 32 ft Telephotometer 149 ft	Source 32 ft Telephotometer 20 ft
Sept. 22, 1947	0.908	0.901	
25	0.693	0.674	
30	0.896	0.896	
Oct. 20	0.792	0.762	
Dec. 8	0.848	0.835	
9	0.734	0.738	
16	0.694	0.712	
Jan. 8, 1948	0.602	0.616	
19	0.862	0.840	
Feb. 16	0.799	0.805	
Apr. 5	0.846	0.824	
8	0.520	0.476	
May 6	0.855	0.871	
11	0.821	0.818	
July 21	0.778	0.778	
Sept. 27	0.833	0.853	
Oct. 27	0.519	0.522	
Nov. 16	0.624	0.610	
23	0.686	0.688	
Jan. 6, 1949	0.855	0.860	
18	0.612	0.612	
25	0.416	0.394	
Mar. 21	0.729	0.735	
	avg 0.736	avg 0.731	
Oct. 22, 1947	0.667		0.661
27	0.880		0.879
Nov. 12	0.815		0.813
20	0.747		0.735
	avg 0.777		avg 0.772

TABLE 2
Atmospheric Transmission Measurements - June 1, 1949*
Luminous Phosphor Button Telephotometer No. 201414
Observer: C. P.

Light Source	Time	Illumination (Sea-Mile Candles)	Transmission Per Sea Mile
Low Search- light, 32 ft above water	2124	165 128 170 137 128	0.820 0.796 0.823 0.803 0.796
Top Search- light, 115 ft above water	2135	77.5 77.5 88.5	0.811 0.811 0.816
Lamp No. 19, 115 ft above water	2143	3.45 3.32 3.32	0.815 0.811 0.811
Lamp No. 14, 115 ft above water	2155	2.09 2.43 2.09	0.803 0.817 0.803

* Atmospheric conditions were fairly stable during the above measure-
  ments. Wind was east about 2 mph. Daylight visual range was 12 to
  15 sea miles at 2030 on June 1, 1949, and 15 sea miles at 0800 on
  June 2, 1949.

TABLE 3
Atmospheric Transmission Measurements - October 25, 1949*
Radium Button Telephotometer No. 201414

Light Source	Time	Observer	Illumination (Sea-Mile Candles)	Transmission Per Sea Mile
Low Search-light, 32 ft above water	1836	M. K.	82.0	0.757
		L. D.	140.0	0.805
		L. D.	69.0	0.741
		E. O.	69.0	0.741
		E. O.	69.0	0.741
	1843	E. O.	98.0	0.773
		C. P.	140.0	0.805
		C. P.	98.0	0.773
		C. P.	109.0	0.781
		M. K.	162.0	0.820
		M. K.	47.0	0.710
		L. D.	82.0	0.757
		L. D.	54.5	0.721
		E. O.	82.0	0.757
		E. O.	69.0	0.741
		C. P.	94.0	0.769
	1851	C. P.	85.0	0.760
		E. O.	85.0	0.760
		E. O.	67.0	0.739
		M. K.	94.0	0.769
		M. K.	64.0	0.736
		L. D.	161.0	0.819
		L. D.	72.0	0.745
		C. P.	105.0	0.779
		C. P.	113.0	0.785
	1905	C. P.	120.0	0.791
		C. P.	132.0	0.800
	1910	M. K.	69.0	0.741
		L. D.	52.0	0.718
		E. O.	74.5	0.750
		C. P.	98.0	0.773
	1915	C. P.	74.5	0.749
		M. K.	54.5	0.722
		M. K.	52.0	0.718
	1919	M. K.	74.5	0.750
		M. K.	54.5	0.722
	1943	C. P.	67.0	0.739
		M. K.	50.0	0.715
Lamp No. 15, 32 ft above water	1951	M. K.	1.52	0.775
		M. K.	1.33	0.763
		M. K.	1.18	0.753
		C. P.	2.10	0.803
		C. P.	1.52	0.775
		C. P.	1.63	0.780
	1955	C. P.	1.52	0.775

* Considerable twinkling occurred during the above measurements. Wind was east about 10 mph. Daylight visual range was 12 to 15 sea miles at 1630 on October 25, 1949, and 16 sea miles at 0800 on October 26, 1949.

PRECISION OF MEASUREMENTS

The principal source of error was the matching of the photometer field by the observer. Table 2 gives sample data of the sort taken on a routine basis. These measurements were made by an experienced observer on a night which was fairly stable. The probable error in a single determination of transmission per sea mile was about ±1 percent.

Table 3 presents a series of measurements taken under adverse conditions when there was considerable twinkling. Four observers were used. Here the variations were considerably greater and the probable error in a single measurement of transmission per sea mile was ±3 percent.

The error in transmission per mile produced from other errors can easily be determined from Equation 2. The total differential of this equation, considering x as a constant and E and C as variables, is

$$\frac{dt}{t} = \frac{1}{x}\left[\frac{dE}{E} - \frac{dC}{C}\right] \tag{4}$$

which gives the relative error in t caused by error in E and C. Thus, taking x as approximately 9 sea miles, the relative error in t is 1/9 that in E or C.

The probable error of the mean value of the illumination E due to calibration of the telephotometer was about ±10 percent; the mean candle power C of the light source was determined with a probable error of about ±5 percent. The error in the distance x was negligibly small since this was measured by U. S. Coast and Geodetic Survey. Hence the total error in t due to errors in E and C was at the most about ±2 percent, due to the above considerations.

Other sources of error were present but it was believed that they were made negligible. Voltage regulators were used to avoid errors caused by voltage changes in the light sources. During operation an operator kept watch on the ammeter reading for each lamp and, by means of a Variac, made necessary adjustments to keep the reading constant. A life test on the 1000-candle-power lamps showed that when the lamp had been properly aged, the candle power remained constant for 230 hours of operation, which was as long as the test was continued. The constancy of candle power is attributed to the fact that the lamps were operated at 2850°K and this operation was at a voltage considerably lower than the normal operating voltage of the lamps. In the case of the searchlights, errors occurred if the lights were not pointed accurately on the telephotometer. Aiming was therefore checked each night of operation by means of the sight on the searchlight.

Another possible source of error was background brightness caused by lights in the neighborhood of the light sources; this would cause a spuriously high telephotometer reading. To avoid the neighboring lights, the field of view was kept small (about 5 minutes of arc) by setting the iris diaphragm in the phosphor telephotometer at nearly the smallest opening. Therefore, neighboring lights on Tilghman Island created no disturbance. Lights of passing ships were avoided by waiting until the ships had passed out of the field of view. On moonlit nights the illumination produced by the background was measured with the light source turned off; then, this illumination was subtracted from the total illumination indicated by the telephotometer before calculating the transmission. This procedure was found quite necessary for the 1000-candle-power filament lamps because the background illumination was an appreciable part of the total illumination. In the case of the searchlights this was not necessary because the background illumination was only a very small fraction of the total illumination.

On very calm nights reflection of the source lights in the water may add to the illumination measured at the receiver. The actual amount of this effect is unknown but is certainly small because the field of view used was 5 to 10 minutes of arc and thus excluded most of the reflections when they occurred. Usually the Bay was not calm enough to show any appreciable reflection of the light sources at such a great distance as 8.77 sea miles.

CONCLUSIONS

An 8.77-sea-mile range has been established at Chesapeake Bay Annex over which visual transmission is measured at night with a precision of about ±2 percent for transmission ranging from 0.4 to 0.9 per sea mile. Lower values could not be read because of instrumental limitations; however transmissions this low occurred but seldom.

There was no correlation between the light transmission and such atmospheric conditions as relative humidity, pressure, temperature, and wind velocity and direction.

The range at CBA is available for use in experiments where a knowledge of visual transmission at night is needed. Examples are: the study of portable transmissometers, the study of spectral attenuation of light by the atmosphere, the testing and operational evaluation of optical communication systems, and the study of aids to night vision.

ACKNOWLEDGMENTS

We gratefully acknowledge the work of C. G. Dilks, who made many measurements and assisted in the calibration of lamps and telephotometers, and R. Scolnik, who assisted in lamp calibrations.

* * *

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